

# Lepton flavor violation in medium energy setup of a beta-beam facility

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## Abstract

We examine lepton flavor violating couplings of the neutrinos to  $W$  boson in medium energy setup of a beta-beam experiment. We show that muon production via quasielastic scattering and deep inelastic scattering processes  $\nu_e n \rightarrow \mu^- p$  and  $\nu_e N \rightarrow \mu^- X$  are very sensitive to  $W\mu\nu_e$  couplings. We perform a model independent analysis and obtain 95% confidence level bounds on these couplings.

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## I. INTRODUCTION

Lepton number ( $L_i = L_e, L_\mu, L_\tau$ ) is conserved in the standard model (SM) with massless neutrinos. However experimental data such as those coming from Super-Kamiokande [1, 2] or Sudbury Neutrino Observatory [3] showed evidence of neutrino oscillations. These experimental results imply lepton flavor violation (LFV) and the lepton sector of the SM requires an extension including massive neutrinos. Since conservation of the lepton flavor number is not a law of nature that we rely on, it is significant to quest for new physics via lepton flavor violating effective operators. Effective lagrangian extension of the SM could have an impact on particle physics and astrophysics. Therefore it is crucial to investigate the physics potential of neutrino experiments to probe LFV.

Neutral-current lepton flavor violating processes such as  $Z \rightarrow \ell_i^\pm \ell_j^\mp$  ( $\ell_i = e, \mu, \tau$ ) can be observable at colliders and effective operators contributing to these processes have been stringently constrained by collider experiments [4, 5]. On the other hand, in colliders neutrinos are not detected directly in the detectors. Instead, their presence is inferred from missing energy signal. Therefore it is impossible to detect a neutrino flavor at a collider and charged-current processes such as  $W^\pm \rightarrow \ell_i^\pm \nu_j$  can not be discerned. In order to constrain lepton flavor violating couplings of neutrinos to  $W$  boson, beta beams provides an excellent opportunity. Beta beams are electron neutrino and antineutrino beams produced via the beta decay of boosted radioactive ions [6]. Such decays produce pure, intense and collimated neutrino or antineutrino beams. Purity of the neutrino beam make it possible to probe couplings  $W\ell_i\nu_e$  with a high precision.

In the original beta beam scenario ion beams are accelerated in the proton synchrotron or super proton synchrotron at CERN up to a Lorentz gamma factor of  $\gamma \sim 100$ , and then they are allowed to decay in the straight section of a storage ring. After the original proposal, different options for beta beams were investigated. A low gamma ( $\gamma = 5 - 14$ ) option was first proposed by Volpe [7]. Physics potential of low-energy beta beams was discussed in detail. It was shown that such beams could have an important impact on nuclear physics, particle physics and astrophysics [8–19]. Higher gamma options for the beta beams have also been studied in the literature [14, 20–29]. A higher gamma factor provides several advantages. Firstly, neutrino fluxes increase quadratically with the gamma factor. Secondly, neutrino scattering cross sections grow with the energy and hence considerable enhancement

is expected in the statistics. An additional advantage of a higher gamma option is that it provides us the opportunity to study deep inelastic neutrino scattering from the nucleus. Very high gamma ( $\sim 2000$ ) options would require modifications in the original plan such as using LHC and therefore extensive feasibility study is needed. In this context medium energy setup is more appealing and less speculative.

In this paper we investigate the physics potential of a medium energy setup ( $\gamma = 350 - 580$ ) proposed in Ref. [20] to probe lepton flavor violating couplings  $W_{\mu\nu_e}$ . As far as we know, phenomenology of LFV in a beta beam facility was studied only in Ref. [30] but considering supersymmetric models. Different from [30] we have probed LFV in a model independent way by means of the effective Lagrangian approach.

The organization of this paper is as follows: In the next section we outline the effective Lagrangian approach. In section III we summarize the neutrino fluxes and the cross sections for quasielastic and deep inelastic scattering and present our main results. Finally Section IV includes concluding remarks.

## II. EFFECTIVE LAGRANGIAN FOR LEPTON FLAVOR VIOLATING $W_{\ell_i\nu_j}$ COUPLINGS

There is an extensive literature on non-standard interactions of neutrinos [29, 31–40]. New physics contributions to lepton flavor violating  $W_{\ell_i\nu_j}$  couplings can be investigated in a model independent fashion by means of the effective Lagrangian approach. The theoretical basis of such an approach rely on the assumption that at higher energies beyond where the SM is valid, there is a more fundamental theory which reduces to the SM at lower energies. The SM is assumed to be an effective low-energy theory in which heavy fields have been integrated out. Such a procedure is quite general and independent of the model at the new physics energy scale.

Specifically we consider the  $SU(2)_L \otimes U(1)_Y$  invariant effective Lagrangian introduced in Refs. [4, 5, 41]. The effective Lagrangian can be written as

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2} \sum_{n,i,j} c_n^{ij} O_n^{ij} + \dots \quad (dim > 6) \quad (1)$$

where  $i, j = 1, 2, 3$  denote flavor indices,  $n$  runs over the number of independent operators of dimension-6 and  $\Lambda$  is the energy scale of new physics.  $c_n^{ij}$  are the dimensionless anomalous

coupling constants. There are four independent operators of dimension-6 contributing to  $W\ell_i\nu_j$  vertex:

$$O_{LW}^{ij} = (\bar{L}_i \gamma^\mu \tau^a D^\nu L_j) W_{\mu\nu}^a + h.c. \quad (2)$$

$$O_{\phi L}^{(3)ij} = i(\phi^\dagger \tau^a D_\mu \phi)(\bar{L}_i \gamma^\mu \tau^a L_j) + h.c. \quad (3)$$

$$O_{D\ell}^{ij} = (\bar{L}_i D_\mu \ell_{Rj}) D^\mu \phi + h.c. \quad (4)$$

$$O_{\ell W\phi}^{ij} = \bar{L}_i \sigma^{\mu\nu} \tau^a \ell_{Rj} \phi W_{\mu\nu}^a + h.c. \quad (5)$$

where  $L_i$  and  $\ell_{Rj}$  are the left-handed lepton doublet and right-handed singlet of  $SU(2)_L \otimes U(1)_Y$ .  $\phi$  is the scalar doublet and  $D_\mu$  is the covariant derivative.  $W_{\mu\nu}^a$  and  $\tau^a$  are the  $SU(2)_L$  gauge boson field tensors and Pauli matrices respectively.

After spontaneous symmetry breaking, operators (2-5) give rise to vertex functions for  $W\ell_i\nu_j$ . The vertex functions for  $W(k)\ell_i(p_2)\nu_j(p_1)$  generated from the effective Lagrangian are given, respectively, by

$$\Gamma_{(1)}^\lambda = c_1 \sqrt{2} [-p_1^\lambda k_\mu \gamma^\mu P_L + p_2^\lambda k_\mu \gamma^\mu P_L - (k \cdot p_2) \gamma^\lambda P_L + (k \cdot p_1) \gamma^\lambda P_L] \quad (6)$$

$$\Gamma_{(2)}^\lambda = -c_2 \frac{g\eta^2}{\sqrt{2}} \gamma^\lambda P_L \quad (7)$$

$$\Gamma_{(3)}^\lambda = -c_3 \frac{g\eta}{2} p_2^\lambda P_L \quad (8)$$

$$\Gamma_{(4)}^\lambda = 2i\eta c_4 k_\rho \sigma^{\rho\lambda} P_L \quad (9)$$

For a convention, we assume that  $p_1$  is incoming to and  $p_2$  and  $k$  are outgoing from the vertex.  $c_i$  ( $i = 1, \dots, 4$ ) are scaled coupling constants defined by:  $c_1 = \frac{c_{LW}}{\Lambda^2}$ ,  $c_2 = \frac{c_{\phi L}^{(3)}}{\Lambda^2}$ ,  $c_3 = \frac{c_{D\ell}}{\Lambda^2}$  and  $c_4 = \frac{c_{\ell W\phi}}{\Lambda^2}$  (For abbreviation we drop flavor indices).  $P_L = \frac{1}{2}(1 - \gamma_5)$ ,  $g$  is  $SU(2)_L$  coupling constant and  $\eta$  represents the vacuum expectation value of the scalar field. (For definiteness, we take  $\eta = 246$  GeV in the calculations presented in this paper).

Operators (2-5) not only contribute to  $W\ell_i\nu_j$  but also  $Z\ell_i^-\ell_j^+$  couplings. On the other hand,  $Z\ell_i^-\ell_j^+$  receive contributions from 9 independent operators [41]. Therefore processes involving  $Z\ell_i^-\ell_j^+$  vertex do not isolate the contributions coming from operators (2-5).

### III. NEUTRINO FLUXES AND CROSS SECTIONS

In a beta beam facility very intense and collimated neutrino or antineutrino beams can be produced by accelerating  $\beta$ -unstable heavy ions to a given  $\gamma$  factor and allowing them to decay in the straight section of a storage ring. In the ion rest frame the neutrino spectrum is given by the following formula

$$\frac{dN}{d\cos\theta dE_\nu} \sim E_\nu^2(E_0 - E_\nu)\sqrt{(E_\nu - E_0)^2 - m_e^2} \quad (10)$$

where  $E_0$  is the electron end-point energy,  $m_e$  is the electron mass.  $E_\nu$  and  $\theta$  are the energy and polar angle of the neutrino. Neutrino flux observed in the laboratory frame can be obtained by performing a Lorentz boost. The neutrino flux per solid angle in a detector located at a distance  $L$  is given by [20]

$$\left(\frac{d\phi^{Lab}}{dSdy}\right)_{\theta \simeq 0} \simeq \frac{N_\beta}{\pi L^2} \frac{\gamma^2}{g(y_e)} y^2 (1-y) \sqrt{(1-y)^2 - y_e^2}, \quad (11)$$

where  $0 \leq y \leq 1 - y_e$ ,  $y = \frac{E_\nu}{2\gamma E_0}$ ,  $y_e = \frac{m_e}{E_0}$  and

$$g(y_e) = \frac{1}{60} \left( \sqrt{1 - y_e^2} (2 - 9y_e^2 - 8y_e^4) + 15y_e^4 \text{Log} \left[ \frac{y_e}{1 - \sqrt{1 - y_e^2}} \right] \right). \quad (12)$$

$^{18}\text{Ne}$  and  $^6\text{He}$  ions have been proposed as ideal candidates for a neutrino and an antineutrino source, respectively [6, 20]. These ions produce pure (anti)neutrino beams via the reactions  $^{18}_{10}\text{Ne} \rightarrow ^{18}_9\text{F}e^+\nu_e$  and  $^6_2\text{He}^{++} \rightarrow ^6_3\text{Li}^{+++}e^-\bar{\nu}_e$ . We assume that total number of ion decays per year is  $N_\beta = 1.1 \times 10^{18}$  for  $^{18}\text{Ne}$  and  $N_\beta = 2.9 \times 10^{18}$  for  $^6\text{He}$ .

Neutrino and antineutrino fluxes as a function of (anti)neutrino energy at a detector of  $L = 732$  km distance are plotted in Fig. 1.  $\gamma$  parameters for ions are taken to be  $\gamma = 350$  for  $^6\text{He}$  and  $\gamma = 580$  for  $^{18}\text{Ne}$ . The foregoing detector distance and  $\gamma$  values have been proposed in Ref. [20] as a medium energy setup. In Ref. [20] authors have considered a Megaton-class water Cerenkov detector with a fiducial mass of 400 kiloton. They show that a cut demanding the reconstructed energy to be larger than 500 MeV suppresses most of the residual backgrounds. We assumed a water Cerenkov detector with the same mass and a cut of 500 MeV for the calculations presented in this paper.

In Fig.1 we observe that neutrino spectrum extend up to 4 GeV and antineutrino spectrum extend up to 2.5 GeV. The energy range of the neutrino spectrum is comparably larger than the antineutrino spectrum. Therefore number of events for antineutrinos is expected to be

low. So we do not perform an analysis for antineutrinos. For neutrino energies between 0.5 - 1.5 GeV, dominant contribution to the cross section is provided by quasielastic scattering. When neutrino energy exceeds 1.5 GeV, deep inelastic scattering starts to dominate the cross section. Neutrino electron scattering takes place at all energies in the spectrum. Lepton flavor violating  $\nu_e e^- \rightarrow \nu_e \mu^-$  process contains both  $W$  and  $Z$  exchange diagrams. Hence this process receives contributions from both  $W\mu\nu_e$  and  $Z\mu e$  couplings. Therefore it is not possible to set limits on  $W\mu\nu_e$  coupling independent from  $Z\mu e$ . Since the main advantage of a beta beam facility has been lost (isolation of the  $W\mu\nu_e$  vertex) we do not analyse the process  $\nu_e e^- \rightarrow \nu_e \mu^-$ .

### A. Neutrino nucleon quasielastic scattering

In addition to SM quasielastic scattering  $\nu_e n \rightarrow e^- p$ , operators (2-5) give rise to new reactions  $\nu_e n \rightarrow \mu^- p$  and  $\nu_e n \rightarrow \tau^- p$ . The tau production threshold is 3.5 GeV. Hence, tau production calls for a higher  $\gamma$  factor and medium energy setup of a beta-beam facility is not convenient to analyse  $\nu_e n \rightarrow \tau^- p$  reaction. On the other hand, muon production via quasielastic scattering seems to be appealing. Feynman diagram for  $\nu_e n \rightarrow \mu^- p$  is given in the left panel of Fig.2. We see from the diagram that hadron current is given by the standard formula [42],

$$J_h^\mu = \frac{g}{2\sqrt{2}} \cos \theta_C \bar{u}_p \left[ \gamma^\mu F_V - \gamma^\mu \gamma_5 F_A + \frac{1}{2m_N} i\sigma^{\mu\nu} q_\nu F_W \right] u_n \quad (13)$$

where  $\cos \theta_C = 0.974$  is the Cabibbo angle,  $m_N$  is the mass of the nucleon and  $F$ 's are invariant form factors that depend on the transferred momentum  $q^2 \equiv (p_p - p_n)^2$ . The  $F$ 's are known as vector  $F_V$ , axial-vector  $F_A$  and tensor  $F_W$  (or weak magnetism) form factors. They are all G-parity invariant. We adopt the same parameterization of the momentum dependence as in Ref. [43]:

$$\begin{aligned} F_V(q^2) &= \frac{1 - \frac{(1+\xi)q^2}{4m_N^2}}{\left(1 - \frac{q^2}{4m_N^2}\right) \left(1 - \frac{q^2}{(0.84 \text{ GeV})^2}\right)^2} \\ F_W(q^2) &= \frac{\xi}{\left(1 - \frac{q^2}{4m_N^2}\right) \left(1 - \frac{q^2}{(0.84 \text{ GeV})^2}\right)^2} \\ F_A(q^2) &= 1.270 \left(1 - \frac{q^2}{(1.032 \text{ GeV})^2}\right)^{-2} \end{aligned} \quad (14)$$

Here  $\xi = (\mu_p - \mu_n)/\mu_N = 3.706$  is the difference in the anomalous magnetic moments of the nucleons. Lepton current generated from the effective vertices (6-9) is given by

$$J_\ell^\lambda = \bar{u}_\mu [\Gamma_{(1)}^\lambda + \Gamma_{(2)}^\lambda + \Gamma_{(3)}^\lambda + \Gamma_{(4)}^\lambda] u_{\nu_e} \quad (15)$$

From (13) and (15) scattering amplitude is obtained as

$$M = \frac{\left(g_{\mu\lambda} - \frac{q_\mu q_\lambda}{m_W^2}\right)}{q^2 - m_W^2} J_h^\mu J_\ell^\lambda \quad (16)$$

where  $m_W$  is the W boson mass. The W propagator can be approximated as;  $\frac{g_{\mu\lambda} - \frac{q_\mu q_\lambda}{m_W^2}}{q^2 - m_W^2} \approx -\frac{g_{\mu\lambda}}{m_W^2}$

In Fig.3 we show total cross section of  $\nu_e n \rightarrow \mu^- p$  as a function of neutrino energy for some values of the anomalous couplings. We see from the figure that cross sections proportional to couplings  $c_1, c_3$  and  $c_4$  have similar behaviors as a function of neutrino energy. They all increase as the energy increases but increment rate is especially high up to 2 GeV. On the other hand, anomalous cross section for  $c_2$  attains its maximum at approximately 1 GeV and then starts to decrease.

## B. Charged-current deep inelastic scattering

When neutrino energy exceeds 1.5 GeV, deep inelastic scattering starts to dominate the cross section. Charged-current deep inelastic scattering of an electron-neutrino from nucleon is described by t-channel  $W$  exchange diagram (right panel of Fig.2). Since quark couplings to  $W$  boson are not modified by operators (2-5) hadron tensor does not receive any contribution. It is defined in the standard form [44]

$$W_{\mu\nu} = \left(-g_{\mu\nu} + \frac{q_\mu q_\nu}{q^2}\right) F_1(x, Q^2) + \frac{\hat{p}_\mu \hat{p}_\nu}{p \cdot q} F_2(x, Q^2) - i\epsilon_{\mu\nu\alpha\beta} \frac{q^\alpha p^\beta}{2p \cdot q} F_3(x, Q^2) \quad (17)$$

where  $p_\mu$  is the nucleon momentum,  $q_\mu$  is the momentum of the W boson propagator,  $Q^2 = -q^2$ ,  $x = \frac{Q^2}{2p \cdot q}$  and

$$\hat{p}_\mu \equiv p_\mu - \frac{p \cdot q}{q^2} q_\mu.$$

The structure functions for scattering on a proton are defined as follows [44]

$$\begin{aligned} F_2^{W^+} &= 2x(d + \bar{u} + \bar{c} + s) \\ F_3^{W^+} &= 2(d - \bar{u} - \bar{c} + s) \end{aligned} \quad (18)$$

The form factors  $F_1$ 's can be obtained from (18) by using Callan-Gross relation  $2xF_1 = F_2$  [45]. The structure functions for scattering on a neutron are obtained from those of the proton by the interchange  $u \leftrightarrow d$ . In our calculations parton distribution functions of Martin *et al.*[46] have been used. We assumed an isoscalar oxygen nucleus  $N = (p + n)/2$  and two free protons for each  $H_2O$  molecule. Naturally occurring oxygen is 99.8%  $^{16}\text{O}$  which is isoscalar [47]. Hence the error incurred by assuming an isoscalar oxygen target would be not more than a fraction of one percent.

Possible new physics contributions coming from the operators (2-5) only modify the lepton tensor:

$$L_{\mu\nu} = \sum_{spin} [\bar{u}(k')\Gamma_\mu u(k)]^\dagger [\bar{u}(k')\Gamma_\nu u(k)] \quad (19)$$

where  $k$  and  $k'$  are the momenta of initial  $\nu_e$  and final  $\mu^-$ , respectively.  $\Gamma_\mu$  represents the sum of anomalous vertices (6-9).

The muon production via charged-current deep inelastic scattering of neutrinos from the proton is plotted in Fig.4. We see from the figure that different from quasielastic scattering case, increment rate is higher at high energies.

### C. Statistical analysis and results

A detailed investigation of the anomalous couplings requires a statistical analysis. To this purpose, number of events have to be calculated. If we assume that initial neutrino beam is pure and contains only electron-neutrinos then SM cross section for muon production is zero. But neutrino beam near the detector should contain a small fraction of muon-neutrinos due to neutrino oscillations. In Fig.5 we present the transition probability  $P(\nu_e \rightarrow \nu_\mu)$  and the survival probability  $P(\nu_e \rightarrow \nu_e)$  as a function of neutrino energy at a detector of distance 732 km. We use the following approximate formulas [48]

$$P(\nu_e \rightarrow \nu_\mu) = \frac{1}{2} \sin^2(2\theta_{13}) \sin^2 \theta_{23} \left( 1 - \cos \left( 2.54 \frac{\Delta m_{23}^2 L}{E_\nu} \right) \right) \quad (20)$$

$$P(\nu_e \rightarrow \nu_e) = 1 - \frac{1}{2} \sin^2(2\theta_{13}) \left( 1 - \cos \left( 2.54 \frac{\Delta m_{23}^2 L}{E_\nu} \right) \right) \quad (21)$$

where  $\Delta m_{23}^2$  is the neutrino mass-squared difference in  $eV^2$ ,  $L$  is the distance between neutrino source and detector in  $m$  and neutrino energy  $E_\nu$  is given in units of  $MeV$ . In the



calculations we assume that  $\sin^2 \theta_{13} = 0.035$ ,  $\sin^2 \theta_{23} = 0.50$  and  $|\Delta m_{23}^2| = 2.40 \times 10^{-3} \text{ eV}^2$  [49]. Number of events has been obtained by integrating cross section over the neutrino energy spectrum and transition probability and multiplying by the appropriate factor that accounts for the number of corresponding particles (protons or neutrons) in a 400 kiloton fiducial mass of the detector. For instance, number of SM events for charged-current deep inelastic scattering is given through the formula,

$$N_{SM} = \int P(\nu_e \rightarrow \nu_\mu) \left( \frac{d\phi^{Lab}}{dS dE_\nu} \right) [N_p \sigma_{\nu_\mu p \rightarrow \mu^- X} + N_n \sigma_{\nu_\mu n \rightarrow \mu^- X}] dE_\nu \quad (22)$$

where  $\sigma_{\nu_\mu p \rightarrow \mu^- X}$  and  $\sigma_{\nu_\mu n \rightarrow \mu^- X}$  are the SM cross sections of deep inelastic scattering of the muon-neutrino from the proton and neutron respectively.  $N_p$  and  $N_n$  are the number of protons and neutrons in a 400 kiloton fiducial mass of the detector. Number of lepton flavor violating events can be calculated in a similar manner but considering lepton flavor violating cross sections and survival probability.

We studied 95% confidence level (C.L.) bounds using one-parameter  $\chi^2$  analysis without a systematic error. The  $\chi^2$  function is given by,

$$\chi^2 = \left( \frac{N}{N_{SM} \delta_{stat}} \right)^2 \quad (23)$$

where  $N$  is the number of lepton flavor violating events as a function of couplings  $c_1, c_2, c_3, c_4$ ,  $N_{SM}$  is the number of events expected in the SM and  $\delta_{stat}$  is the statistical error. In Table I, we show 95% C.L. bounds on the couplings  $c_1, c_2, c_3$  and  $c_4$  obtained from quasielastic and deep inelastic scatterings. These bounds are obtained for 1 year running time of the beta-beam experiment. We see from the table that bounds obtained from quasielastic and deep inelastic scatterings are close to each other. Therefore, they have almost same potential to probe LFV.

#### IV. CONCLUSIONS

Beta beams present an ideal venue to measure neutrino cross sections. For beta beams neutrino fluxes are precisely known and therefore uncertainties associated with the neutrino (antineutrino) fluxes are negligible. Purity of the produced (anti) electron-neutrino beam is an other advantage of beta beams. These features enable to detect neutrino cross sections with a high precision.

Medium energy setup of a beta-beam facility provides us the opportunity to isolate  $W\mu\nu_e$  vertex which is not the case for a collider experiment. Probing  $W\mu\nu_e$  couplings is important for understanding the physics beyond the SM and contributes to the studies in neutrino physics. In neutrino oscillation experiments, identification of the neutrino flavor is based on charged-current processes at the detector. Neutrino flavor can be identified through the flavor of the associated charged lepton. Hence, lepton flavor violating couplings of the neutrinos to  $W$  can mimic the oscillation signals. Therefore constraints on  $W\mu\nu_e$  couplings are important for precision measurements of the oscillation parameters.

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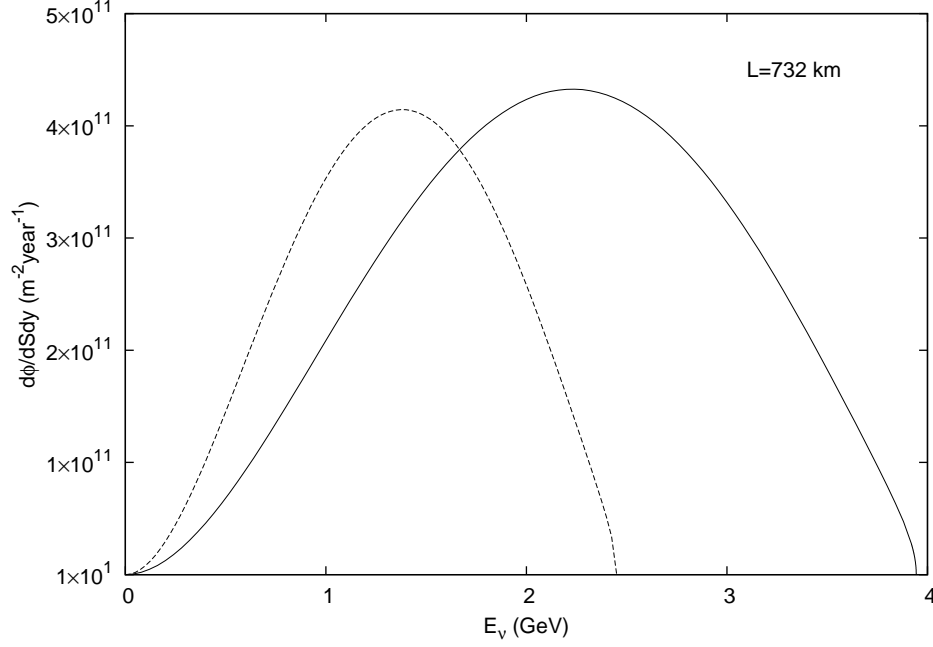


FIG. 1: Fluxes as a function of neutrino energy for  $\nu_e$  (solid line) and  $\bar{\nu}_e$  (dotted line) at a detector of  $L = 732$  km distance.  $\gamma$  parameter is taken to be 350 for  $\bar{\nu}_e$  and 580 for  $\nu_e$ .

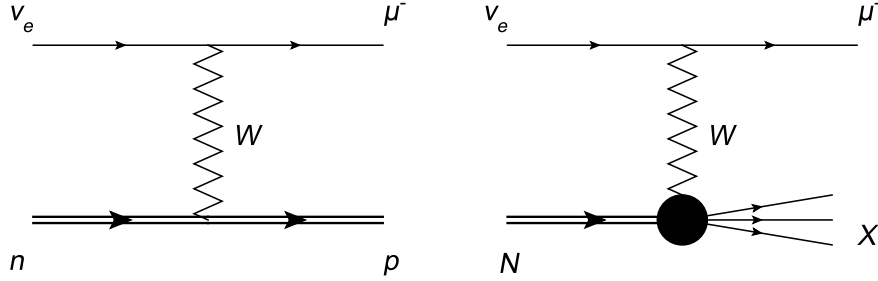


FIG. 2: Figure on the left shows Feynman diagram for  $\nu_e n \rightarrow \mu^- p$ . Figure on the right represents schematic diagram for neutrino deep inelastic scattering  $\nu_e N \rightarrow \mu^- X$ .

TABLE I: 95% C.L. bounds on the couplings  $c_1, c_2, c_3$  and  $c_4$  obtained from quasielastic and deep inelastic scatterings. Only one of the couplings is assumed to be non-zero at a time.

Quasielastic scattering:				
$ c_1  < 0.0159$	$ c_2  < 8.457 \times 10^{-7}$	$ c_3  < 0.0010$	$ c_4  < 8.561 \times 10^{-5}$	
Deep inelastic scattering:				
$ c_1  < 0.0105$	$ c_2  < 8.902 \times 10^{-7}$	$ c_3  < 0.0010$	$ c_4  < 7.846 \times 10^{-5}$	

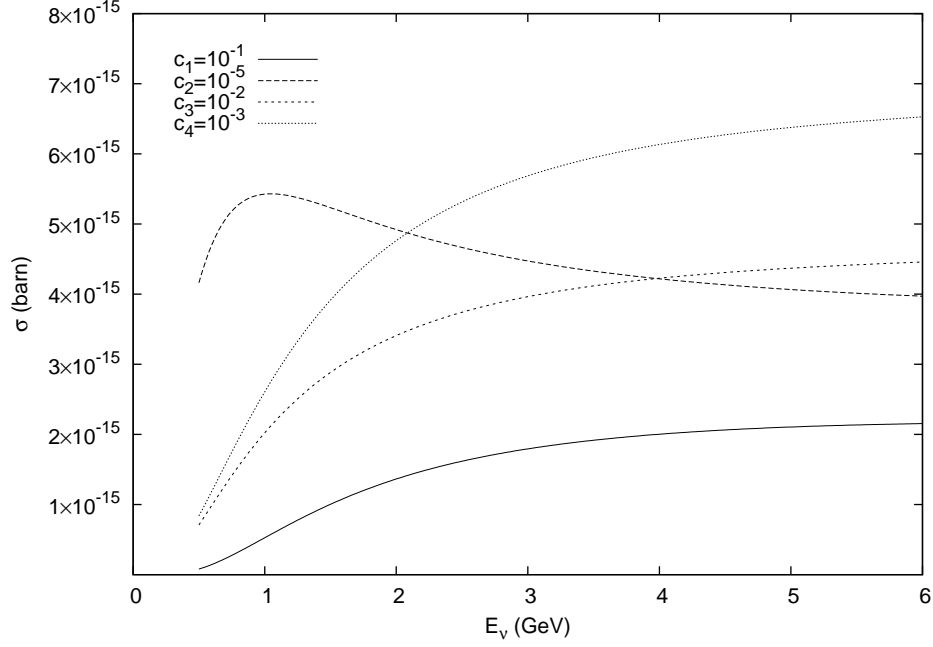


FIG. 3: Total cross section of  $\nu_e n \rightarrow \mu^- p$  as a function of neutrino energy. The values of the anomalous couplings is stated in the figure.

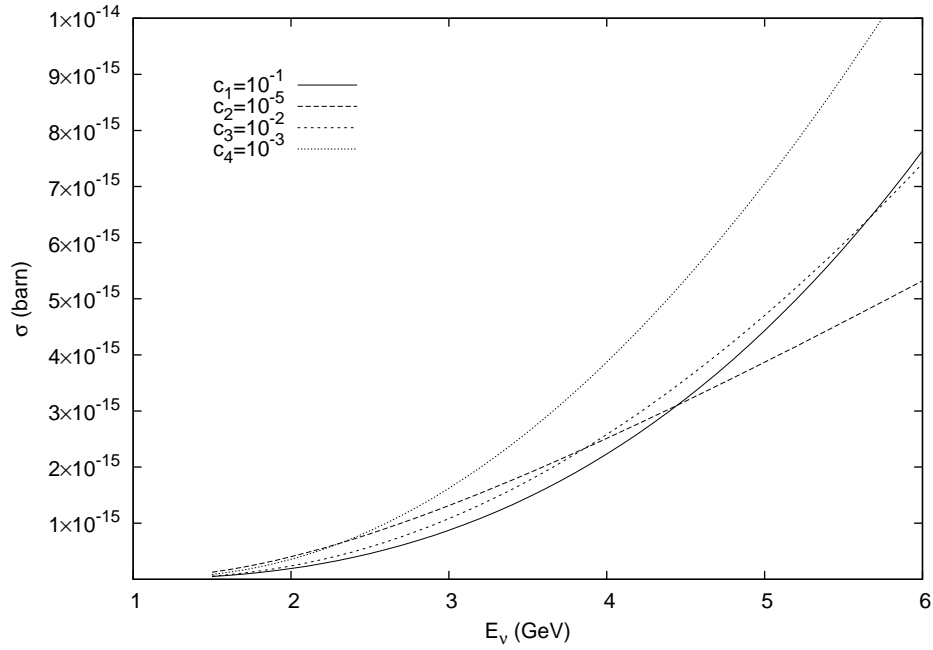


FIG. 4: Total cross section of charged-current deep inelastic scattering  $\nu_e p \rightarrow \mu^- X$  as a function of neutrino energy. The values of the anomalous couplings is stated in the figure.

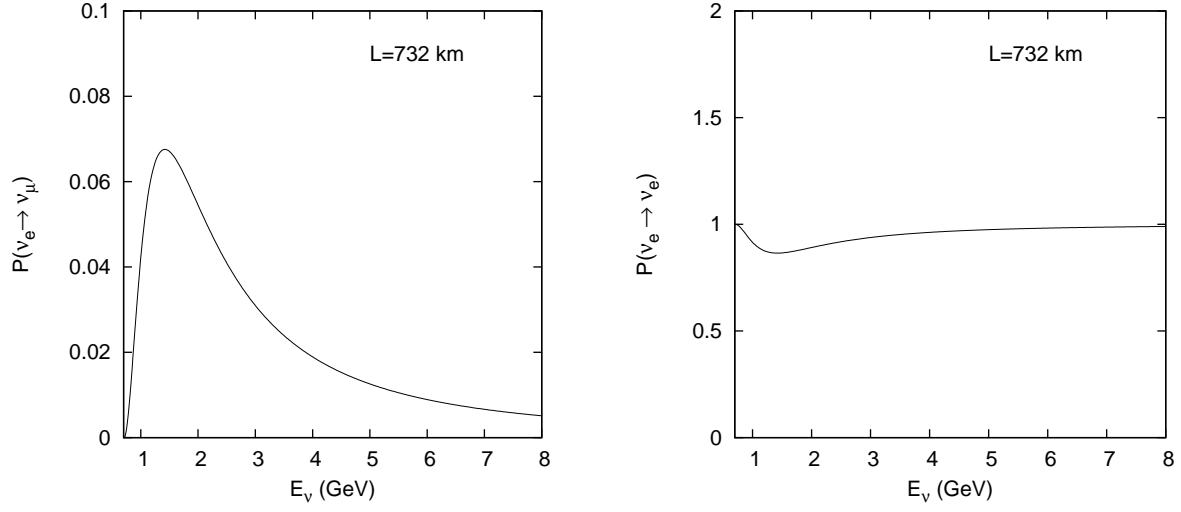


FIG. 5: Figure on the left is the transition probability  $P(\nu_e \rightarrow \nu_\mu)$  and figure on the right is the survival probability  $P(\nu_e \rightarrow \nu_e)$  in vacuum as a function of neutrino energy. Detector distance is taken to be 732 km.